8 Industry and waste management

What is covered in this chapter?

Products manufactured by industry form an essential part of modern economies. Industrialization is a step in the development of countries that brings jobs and better living standards. Industrial production will therefore keep rising and will increasingly be located in developing countries. Interestingly, the most modern installations are often found in developing countries. Since industry contributes about 20% to global greenhouse gas emissions, any serious attempt to reduce global GHG emissions will have to involve industry. Using less energy intensive industrial goods like steel by making lighter cars for instance and using wood for constructing buildings instead of steel, concrete, and bricks is one way to go. Most of the emissions reduction will have to come from more efficient production (less greenhouse gas emissions per unit of product), shifting to low carbon energy sources, and using CO_2 capture and storage to remove CO_2 at the smokestack. For the most important processes the reduction opportunities are discussed. Government policies are needed to make these reduction opportunities a reality. Experience with various policy instruments shows that for big reductions in emissions more stringent instruments, such as cap and trade and regulations, will be needed. Voluntary agreements do initially help to raise awareness amongst participants and to encourage corporate responsibility, but delivering major emission reductions through voluntary agreements is not possible.

Waste is an important emission source in industry and for household and commercial waste. There are strong interactions via recycling of paper, glass, and metals. That is why greenhouse gas emissions and waste are discussed in this chapter together. Waste contributes a few per cent to global emissions. Greenhouse gas emission reduction often goes hand-in-hand with proper waste management for sanitary reasons.

Trends in industrial production

Industry covers a large number of products that are essential for modern economies: food products, building materials like cement, concrete and construction wood, iron and steel,

Table 8.1. **Production of steel (2006) and cement (2005)**

Country	Steel production (Mt/year)	Share of global (%)	Cement production (Mt/year)	Share of global (%)
China	419	34	1064	47
EU	210	17	230	10
Japan	116	9	74	3
USA	98	8	99	4
Russia	71	6	45	2
South Korea	48	4	50	2
India	44	4	130	6
Ukraine	41	3	n/a	n/a
Brazil	31	2	39	2
Turkey	23	2	38	2
World	1242		2284	

Source: IEA Sectoral approaches to greenhouse gas mitigation: exploring issues for heavy industry, 2007.

aluminium and other metals, glass, ceramics, fertilizers, chemicals, paper and cardboard, oil products, cars and other transport means, computers and computer chips, electrical equipment, machinery, and many others. As a result of increased population and economic growth the production capacities of these various industries have increased tremendously. Since 1970, global production of cement increased about threefold, while aluminium, paper, ammonia (for fertilizers), and steel production approximately doubled These are the most energy intensive industries, contributing most to global greenhouse gas emissions.

Much of the production of these energy intensive goods is now located in developing countries. China is the world's largest producer of steel, cement, and aluminium. Developing countries together produced 42% of steel, 57% of nitrogen fertilizer, 78% of cement, and 50% of aluminium in 2003[1]. Production is concentrated in a limited number of countries. China, the EU, Japan, USA, Russia, South Korea, and India account for 82% of the steel and 74% of the cement production in the world (Table 8.1). Many industrial goods are traded globally. Of all aluminium produced, about 75% is traded. For steel it is about 30% (not counting products made with steel); for paper products about the same. For many other industrial products like metals, chemicals, or paper, plants are located where raw materials are readily available, leading to large trade volumes of the manufactured products. For heavy and bulky materials like cement where raw materials are readily available in many places, trading is limited (about 5%). Many manufactured products with limited energy contents (and relatively small emissions) are produced in places with low labour costs. International competition therefore plays a role for a limited set of energy intensive products and that has implications for emission reduction policies.

Since many of the plants in developing countries are relatively new, they are often the most efficient. The reason is that cost minimization is a dominant issue in these internationally competing industries and efficiency (of energy or raw material use) is directly affecting costs. For steel, cement, aluminium, and fertilizer, energy costs are typically 10–20% or more of total costs. For chemicals, paper, ceramics, and glass it is in the order of 5%, still a significant amount and worth reducing. For products like transportation equipment, textiles, food, electrical equipment, and machinery it is less than 2%[2], and incentives for efficiency improvement are less. Energy use per tonne of product has therefore gone down substantially over time in those industries where energy costs are high (see Figure in Box 4.1).

Globally, large companies dominate the energy intensive industry sector. Cement production in China is an exception: there are more than 5000 plants with an average production of not more than 200 000 tonnes/year. In developing countries small and medium sized companies (SMEs) can have a significant share in production, such as in the metals, chemical, food, and paper industries. These SMEs often use older, less efficient technologies and do not have the capacity to invest in modern equipment and emission controls.

Demand for industrial products is expected to increase strongly: for cement a doubling by 2020 and a fourfold increase by 2050.

Trends in waste management

Waste can be separated into industrial waste, which is a by-product of manufacturing, and household/commercial waste, which is the remains of consumption (often called post consumer waste). They are very different in nature: industrial waste is very process specific and can consist of hazardous materials, while post-consumer waste is mostly organic material, wastewater, paper, plastic, metals, and textiles. Construction waste is usually counted under industrial waste. Treatment of waste is also different. In industry recycling of waste streams is an economic necessity. Sending waste off-site for treatment can cost a lot of money. For post-consumer waste collective treatment of waste water and solid waste is a matter of improving health conditions. Keeping as much valuable material out of the solid waste stream as possible is attractive for use as raw materials in industrial glass, paper, and steel production and is widely practised. The small quantities of hazardous waste from households and offices are kept separate as much as possible to avoid spreading these substances in the environment.

Post-consumer waste is increasing with increasing income. In low income countries it is less than 100 kg per person per year. In high income countries it is more than 800 kg. Total solid waste volumes have therefore increased significantly. Currently they are about 900–1300 million tonnes per year globally[3]. The way solid waste is treated varies enormously across countries. In total more than 130 million tonnes (10–15%) is incinerated, often with energy recovery[4]. Roughly 50% is put in landfills (controlled or uncontrolled) and the rest is recycled. Waste water is increasing with income as well, not least because 40% of the world population still has no sewerage connection, septic tank, or latrine in their homes.

To improve health conditions, this situation needs to be addressed urgently.

Greenhouse gas emissions

The industry sector accounts for emissions of about 9.5 $GtCO_2$-eq per year (about 20% of the total). Waste management adds another 1.3 $GtCO_2$-eq or 3% of the total (see Figure 8.1). This excludes the emissions of the electricity used inside industry plants but generated outside (called indirect emissions). These emissions are counted towards the energy supply sector and are about 2.5 $GtCO_2$-eq/year. The share of industry in a country's total emissions varies considerably, even amongst industrialized nations (see Figure 8.2). If indirect emissions are included industry is responsible for about two-thirds of China's total CO_2 emissions.

About 5% of industry and 95% of waste management emissions are from non-CO_2 greenhouse gases: in industry mostly fluorinated gases and some N_2O; in waste management largely CH_4 and a little N_2O. Solid waste landfills generate most of the CH_4 from waste. Waste water treatment generates N_2O and CH_4.

The contribution of specific industry sub-sectors is shown in Figure 8.3.

Future emissions

Greenhouse gas emissions from industry are projected to increase by 20–65% until 2030. For waste management the increase is about 30%, ranging from about zero for N_2O from waste water treatment to about 50% for CH_4 emissions from landfills[5].

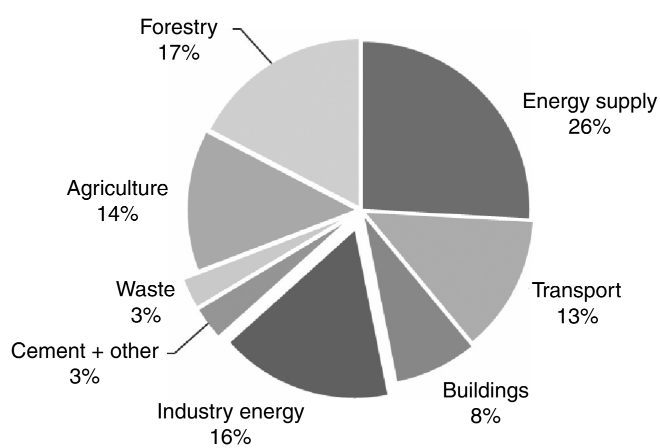

Figure 8.1 **Industry and household/office waste management sector emissions. These are direct emissions only (i.e. excluding the emissions from electricity used in the plant but generated outside). Emissions are separated into energy related emissions from industry, cement and other non-energy related emissions, and waste management emissions.**

Source: IPCC Fourth Assessment Report, Working Group III, ch 1.

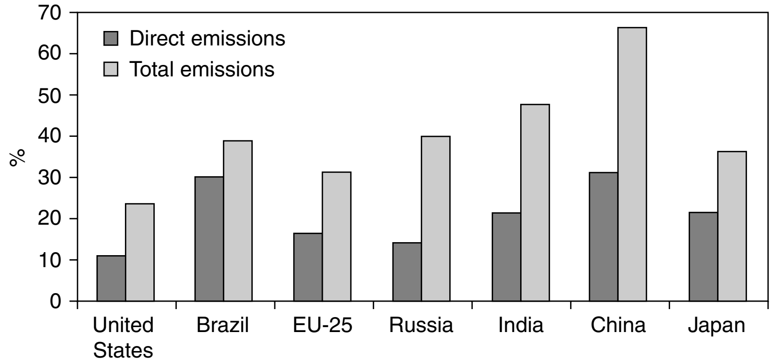

Figure 8.2 **Share of industry in total CO_2 emissions. Both direct and indirect emissions are shown.**
Source: Houser et al. Levelling the carbon playing field, Peterson Institute for International Economics and WRI, 2008.

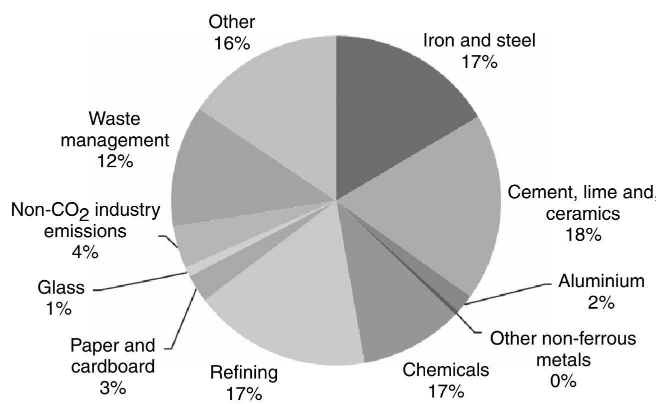

Figure 8.3 **Contributions of subsectors to industry and waste management greenhouse gas emissions in 2004/2005. Includes direct CO_2 and non-CO_2 emissions only.**
Source: IPCC Fourth Assessment Report, Working Group III, ch 7 and IEA Energy Technology Perspectives, 2008.

Opportunities to reduce emissions

Emissions reduction in the industry sector can in principle be achieved in three ways:

1. Replacing energy intensive products with low emission alternatives (e.g. replacing steel and concrete for buildings with wood)
2. Reducing the amount of industrial products consumed (e.g. by producing lighter cars requiring less steel)
3. Reducing the emissions per unit of product by modifying the production process

For waste management this ‘hierarchy’ of options is slightly different: (1) reducing waste volumes; (2) recycling waste; or (3) managing it with lower emissions of greenhouse gases per unit of waste.

Quantitative data on the first two industry options are scarce. However, there is a clear trend towards reducing weight per unit of product in automobile manufacturing, computers, TV sets, packaging, and many other products. It is a matter of becoming more efficient with raw materials (and saving costs) as well as shifting to lighter and cheaper materials. Examples include using thinner material in aluminium cans and steel tins and replacing steel in automobiles with lighter metals and plastics. Due to the strong increase in demand the total amount of material used (and therefore the emissions from production) keeps going up.

Data on the emissions per unit of product are available for many countries and production processes, allowing international comparisons. Very often these comparisons are made in energy use per unit, which can give a very different picture from emissions per unit (see Box 8.1). For the industrial processes that produce most greenhouse gas emissions (iron and steel, cement, and chemicals, together good for about three-quarters of the total emissions from the industry sector) the opportunities for emission reduction through process modifications will be discussed in detail. For some other processes the options will be summarized. In addition, there are many reduction options that apply across the whole sector. These will be discussed separately.

Box 8.1 Energy efficiency and carbon efficiency

Efficiency of industrial installations is often evaluated in terms of energy use per unit of product (energy efficiency). This is because energy costs are an important factor in operating these processes. When comparing installations from a climate change point of view the CO_2 emission per unit of product (or carbon efficiency) is more relevant. This requires one look at the carbon content of the sources of energy used, including the way the electricity is generated that comes from outside the plant.

Iron and steel

There are three different steel making processes (see schematic diagram in Figure 8.4):

1. Reduction of iron ore in blast furnaces, usually with coal (in the form of coke[6]) and conversion of the so-called ‘pig iron’ into steel in a Basic Oxygen Furnace. About 60% of the steel in the world is produced this way
2. Melting of recycled iron (so-called ‘scrap’) in Electric Arc Furnaces (35%)
3. Direct reduction of iron ore with natural gas and further processing it in an electric furnace (5%)

In terms of energy use and CO_2 emissions the traditional blast furnace/basic oxygen furnace process is the worst. Scrap melting (Electric Arc Furnace) only uses about 30–40% of the energy of the traditional process, with CO_2 emissions depending on the source of the electricity. The Direct Reduction/Electric Arc Furnace process (using natural gas) only produces 50% of the CO_2 emissions per tonne of steel compared to the traditional process.

Emissions per tonne of steel in different countries vary considerably, from about 1 to 3.5 tCO_2 per tonne of steel. This is caused by different production processes, sources of electricity, efficiency of equipment, and types of products. Figure 8.5 shows the average CO_2 emissions per tonne of steel for various countries. Both the direct emissions

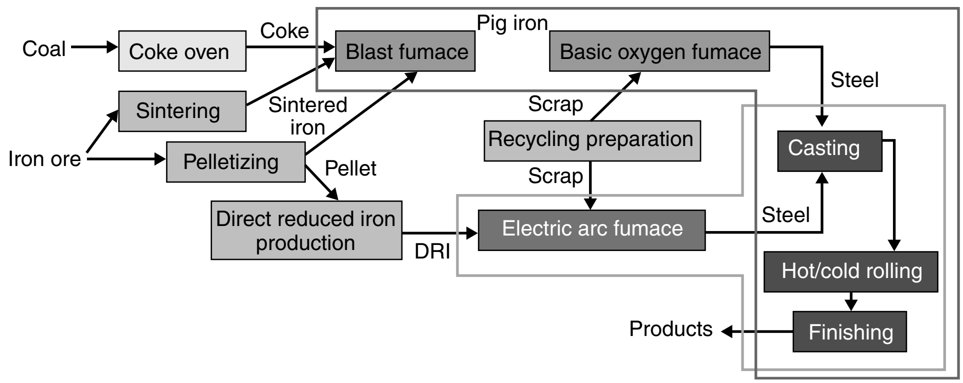

Figure 8.4 **Simplified diagram of the main steel making processes.**

Source: IEA, Assessing measures of energy efficiency performance and their application in industry, 2008.

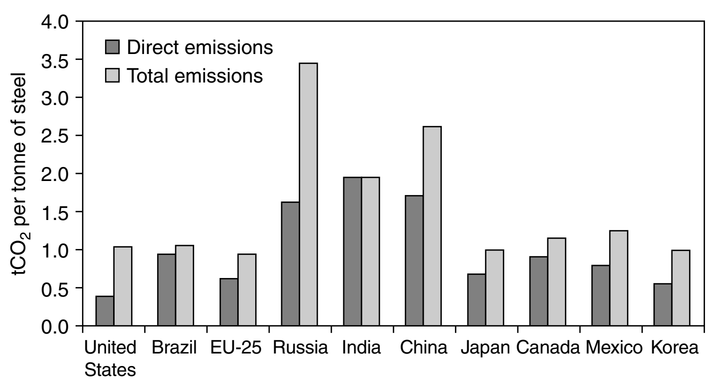

Figure 8.5 **Carbon intensity of steel production, expressed as tCO_2 per tonne of steel. Direct emissions only cover emissions produced at the steel plant. Total emissions also include emissions from coke production and electricity generation off-site.**

Source: Houser et al. Levelling the carbon playing field, Peterson Institute for International Economics and WRI, 2008.

(from the process itself), as well as the indirect emissions (from the production of coke and electricity generated off-site) are given here. The high emissions in India and China are caused by the fact that steel production is overwhelmingly of the Blast Furnace/Basic Oxygen Furnace type, because of insufficient recycled (scrap) iron.

Apart from shifting to production processes with lower emissions (i.e. those that use more scrap iron) there are many opportunities for improving the energy efficiency of the blast furnace and process steps. Adding these up gives efficiency improvement potentials like 15% for Japan and 40% for China when compared with best practices currently found in major steel producing countries[7]. More advanced energy efficiency options are being studied.

Another important way to reduce emissions is to shift from coal (in the form of coke) to a lower carbon reducing agent. Oil, natural gas, waste plastics, and biomass are being used. In Brazil charcoal is used in blast furnaces, but this is unlikely to be from a sustainable source, so net CO_2 emissions are in fact much higher. The use of hydrogen is being investigated for future use, which could bring down emissions considerably. For Electric Arc Furnace processes CO_2 can be reduced by moving to a low carbon electricity source. Recovery of combustible gas that is produced during coke and steel manufacturing can also contribute to emission reductions in places where that is not yet done.

Finally it is technically feasible in principle to apply CO_2 Capture and Storage (CCS, see also Chapter 5). Where applied it could reduce something like 85–90% of the CO_2 emissions. Costs of this reduction option in blast furnaces are relatively high (US$40–50/t$CO_2$ avoided) and CCS has therefore not yet been applied commercially in steel making. Small scale demonstrations are being done and plans exist for large scale demonstrations by 2015. In direct reduction (DRI) plants costs would be lower (US$25/t$CO_2$ avoided), but DRI capacity is still relatively small. By 2030 the CCS reduction potential is estimated at 0.1–0.2 GtCO_2/year, but this could grow to 0.5–1.5 GtCO_2/year in 2050[8].

The worldwide mitigation potential of all options by 2030 at costs of US$20–50/t$CO_2$ avoided is estimated at 15–40%, or 0.4–1.5 GtCO_2/year.

In the longer term, new, so-called 'melt reduction' processes are expected to deliver further reductions. These processes integrate the iron ore preparation, coke making, and blast furnace iron making steps. That increases the energy efficiency and also produces gases with higher CO_2 concentrations that make CCS more attractive. By replacing air with pure oxygen the CO_2 content of the gases can be further increased to make CCS even more attractive. By 2050 these new processes in combination with CCS could deliver an additional 0.2–0.5 GtCO_2/year reduction. The other long term option is to move to different methods of steel processing. Currently steel is first cast into slabs, which are later reheated to be rolled into steel plates and other steel products. By integrating these steps (so-called 'direct casting') significant energy savings can be made.

Cement

The principal component of cement, called clinker, is produced by heating limestone with some additives to high temperatures of about 1500°C. In the process CO_2 is released from the limestone, good for about half of the CO_2 emissions from cement manufacture. The energy used for heating the oven (called a kiln) is also a major source of CO_2 emissions. In the USA, China, and India the energy comes mostly from coal. In Canada, Brazil, and Europe large amounts of biomass are used. The type of kiln also has a big influence. So-called 'wet kilns', with a high moisture content, use 25–125% more energy than dry kilns. Wet kiln processes are predominantly found in Russia, India, China, and Canada. Europe, Japan, Thailand, and Korea mostly use dry kilns.

The additional process steps are also energy intensive. The limestone has to be dug out of a quarry and ground. After that it is pretreated (dried and ground). At the end of the process the clinker is cooled, ground, and other materials are added to get the final cement product (see diagram Figure 8.6).

Emissions per tonne of cement vary from country to country (see Table 8.2).

Since clinker production is the major source of emissions, the clinker content of cement to a large extent determines the emissions per tonne. Standard, so-called Portland, cement contains 95% clinker. In blended cement some of the clinker is replaced by alternative materials, such as fly ash from coal fired power plants, waste material (slag) from blast furnaces, and natural volcanic minerals (pozzolanes). This results in lower CO_2 emissions per tonne of cement. Blended cements are used widely in Europe, but hardly at all in the USA. Replacement of clinker contributes about 30% to current reduction potential, based on best available technologies[9].

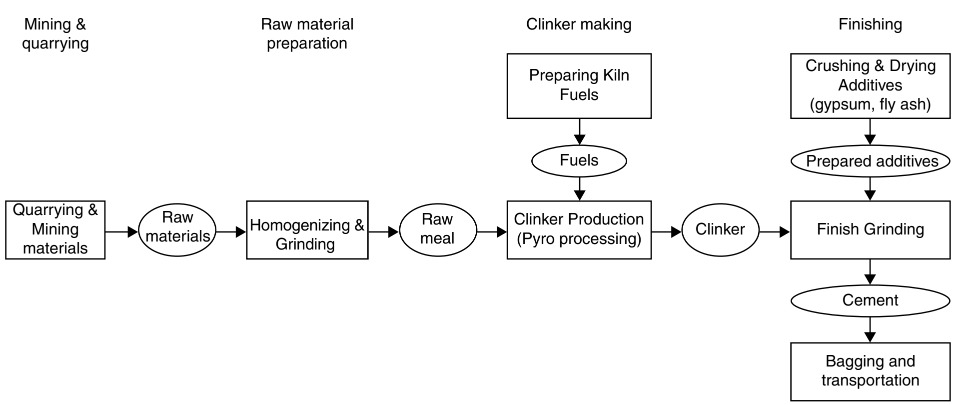

Figure 8.6 **Schematic diagram of cement production.**

Source: Ecofys, Sectoral Approach and Development, Input paper for the workshop 'Where development meets climate', 2008, http://www.pbl.nl/en/dossiers/Climatechange/Publications/International-Workshop-Where-development-meets-climate.html.

Table 8.2. Selected emission intensities of cement (2000 data)

Country	Average emissions (tCO_2/t cement)
Europe	0.70
Japan	0.73
South Korea	0.73
China	0.90
India	0.93
USA	0.93

Source: IPCC Fourth Assessment Report, Working Group III, ch 7.4.5.1.

The efficiency of the kiln and the fuel used to heat the kiln are also important in reducing emissions. As indicated above, the energy use per tonne of cement in dry kilns is lower than in wet kilns. Compared to best available technologies, emissions per tonne of cement can be reduced by about 40%. Shifting from coal to waste materials, including tyres, plastics and biomass, can contribute up to 20% to emission reduction. More efficient use of electricity and lowering the carbon content of electricity used in the process (often generated off-site) can contribute the rest (in the order of 10%).

Cement kilns produce gas streams with high CO_2 concentrations, originating from fuel and limestone. This makes cement plants a good candidate for CO_2 capture and storage (CCS, see also Chapter 5). Since costs would be high (initially more than US\$100/tCO_2 avoided, over time to be reduced to US\$50–75), CCS in cement plants has not yet been applied, nor are there any large demonstration units. With increasing CO_2 prices it is estimated that about 0.25 $GtCO_2$ could be reduced economically by 2030 with CCS in the cement industry at costs of US\$50–100/tCO_2 avoided[10].

For the whole cement sector the estimate of the worldwide mitigation potential at costs up to US\$50/tCO_2 avoided is about 10–40% of the emissions in 2030, or 0.5–2.1 $GtCO_2$/year.

Chemicals and petroleum refining

The chemical industry is very diverse. It covers tens of thousands of products, with annual production varying from a few tonnes to more than 100 million tonnes. The industry covers thousands of companies. Plants are often integrated with petroleum refineries, because oil products are an important raw material. There are more than 700 refineries in 128 countries.

A small number of processes are responsible for about 70% of the energy use in the chemical industry:

1. Ethylene (used mainly for producing plastics), produced by so-called steam cracking (high temperature heating with steam) of oil or gas. Important by-products are propylene (also used for plastics), and aromatic hydrocarbons like benzene. Emissions are about 0.2 $GtCO_2$/year.
2. Methanol, used as an industrial solvent, antifreeze and basis for gasoline additives, produced mainly from natural gas

3. Ammonia, used mainly as a raw material for nitrogen fertilizers. It is produced by reacting nitrogen with hydrogen (produced from gas or coal)

Most of the emissions are in the form of CO_2. Of all the fossil fuel used about half is burned for heating purposes. The other half is used as so-called feedstock for the processes and converted into products. Since many of these products are burned or decomposed with a certain delay, eventually all of the feedstock ends up as emissions of CO_2.

There are some chemical processes that produce significant quantities of non-CO_2 GHGs as by-products from the production process. An important one is N_2O emissions from plants that produce raw materials for the manufacture of nylon and nitric acid. Another major contribution is fluorinated gas (HFC-23) as a by-product of the manufacture of a liquid used in air conditioners (HCFC-22).

Emission reduction opportunities in ethylene manufacture are twofold: (1) energy efficiency improvements in the various stages of the process (cracking, separation); and (2) feedstock choice, affecting the energy required for the cracking process. Energy use per tonne of ethylene has been reduced by about 50% since 1970. This can be further improved by at least 20% for cracking and 15% for the separation processes by applying higher temperature furnaces, combined heat and power gas turbines, and advanced refrigeration systems.

In ammonia production, reduction opportunities are found in efficiency of energy use, the choice of feedstock for making hydrogen, and the application of CCS. Energy efficiency of ammonia plants has already been improved so much that the most recent plants are performing close to the theoretical minimum energy consumption levels (see Figure 8.1 above). Replacing and upgrading existing plants remains to be done.

Hydrogen, one of the main inputs for ammonia manufacture, is produced from natural gas (77% of ammonia production), gasified coal (14%, mainly in China), or oil products (9%). The amount of CO_2 produced by the hydrogen manufacture process makes a big difference in the total CO_2 emission per tonne of ammonia (which varies from 1.5 to 3.1 tCO_2/t ammonia). Moving to a low carbon hydrogen source is therefore an important reduction measure. Adding CO_2 capture and storage (CCS) is the cheapest way to do that, because in the hydrogen plant the CO_2 has already been separated from hydrogen and the expensive capture step can thus be skipped (see Chapter 5). Costs are estimated to be about US$25/$tCO_2$ avoided, which is much lower than producing low-carbon hydrogen from biomass or from electrical decomposition of water. The effect of this reduction option is somewhat limited by the partial use in many ammonia plants of the CO_2 stream for producing urea, a popular fertilizer.

Refineries

Petroleum refineries cannot easily be compared across countries, because there are too many differences in crude oil type, set of products, and equipment. There are however significant opportunities for energy efficiency improvement. Refineries use 15–20% of the energy in crude oil for their operation, leading to current emissions of about

1.9 $GtCO_2$-eq/year. The reduction potential from improving energy efficiency is estimated at 10–20%, representing about 0.3 $GtCO_2$/year. CCS provides additional opportunities of around 0.1 $GtCO_2$/year by 2030.

Non-CO_2 greenhouse gases

Non-CO_2 emission reduction potential is considerable. For many sources in the chemical industry emission reductions of 50–90% are achievable by 2030 at costs lower than US\$20/tCO_2-eq avoided. N_2O from nitric and adipic acid and caprolactam manufacture for instance can be reduced by more than 80% at practically zero cost. More than 80% of HFC-23 emissions can be destroyed by incinerators at costs of less than US\$1/tCO_2-eq. Because of the high Global Warming Potential (GWP) of HFC-23 (see Chapter 2) the small amount destroyed represents a significant amount in terms of CO_2-eq (see Chapter 12 for a discussion of this very cheap option and the implications for the Kyoto Protocol implementation). In total about 0.2–0.3 $GtCO_2$-eq/year can be reduced at relatively low cost.

Altogether, the chemical and petroleum refinery industry can reduce at least 1 $GtCO_2$-eq/year, about 75% at costs below US\$20/tCO_2-eq avoided.

In the longer term significant CO_2 emission reductions can be expected in the chemical industry by shifting to biomass as feedstock, instead of petroleum products, and by using biological or enzymatic processes that can operate at lower temperatures. Reduction percentages of up to 60% would be possible by 2050.

Other industries

Manufacturing of aluminium, magnesium and other metals, paper and cardboard, glass, bricks and ceramics production, and food processing can contribute significantly to the industry reduction potential.

Aluminium

Aluminium production is a highly energy intensive process. Bauxite aluminium ore is refined to aluminium oxide in a high temperature oven. Then the aluminium oxide is reduced to aluminium metal with carbon electrodes in a hot ‘reverse battery’, filled with molten fluoride containing minerals. This process produces large amounts of CO_2, just as in iron ore reduction, but also perfluorinated carbon compounds (PFCs) with a very high GWP. Reduction opportunities lie in more efficient use of energy. The average amount of electricity consumed per unit of product has gone down about 10%

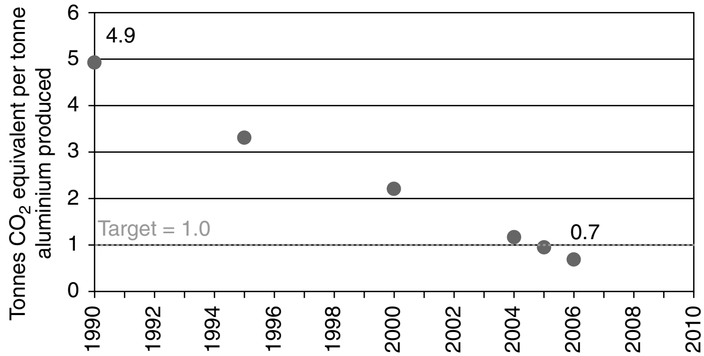

Figure 8.7 PFC emissions from aluminium manufacture 1990–2006.
Source: International Aluminium Institute, 2007 Sustainability report.

over the last 25 years but more is possible. PFC production per tonne of aluminium has gone down by about 85%, stimulated by a voluntary programme implemented by the aluminium industry (see Figure 8.7). Costs of these measures have been low to zero. So-called secondary aluminium smelters use recycled aluminium and have much lower emissions. Increasing the recycling rates (currently about 50%) is therefore an attractive reduction measure. The reduction potential from aluminium manufacturing by 2030 is about 0.1 $GtCO_2$-eq/year. In the longer term processes with non-carbon electrodes could further reduce emissions by 0.1–0.2 $GtCO_2$/year.

Other industries

Other energy intensive industries, like paper and cardboard (usually called pulp and paper), food processing, and glass manufacturing have good mitigation opportunities as well. Energy efficiency improvement is of course a primary one. Management of process waste is another. Anaerobic waste water treatment with methane recovery for energy, use of biomass waste as fuel, and gasification of wood pulping waste for fuel are prominent options to reduce greenhouse gas emissions. In these industries that use a lot of heat for their processes, combined heat and power (CHP) units can make a major contribution (see Chapter 5). Surplus electricity from these CHP units can be exported off-site. Table 8.3 gives a summary of the major mitigation measures. The total mitigation potential in these industries is at least 0.3–0.4 $GtCO_2$/year.

Non-CO_2 gas reduction potential from these other industries is about 0.1 $GtCO_2$-eq/year. SF_6 from magnesium production can be reduced by almost 100% at negative costs. Various fluorinated gases from semiconductors and LCD TV and computer screens manufacture can be reduced by at least 10% at zero costs through recycling and alternative compounds. HFCs, which were introduced as alternatives for ozone depleting fluorinated gases in foam production, refrigeration and air conditioning, or solvent applications, can be replaced with alternatives that have a low GWP or have no greenhouse gas effect (see Box 8.2).

Table 8.3. Main mitigation opportunities in some energy intensive industries

Industry	Main mitigation opportunity
Pulp and paper	Use of waste biomass fuel
	Combined heat and power
	Gasification of wood pulping waste (black liquor) for fuel use
	Increased recycling
Food processing	Energy efficiency improvement
	Combined heat and power
	Methane recovery from waste water
Glass	Energy efficiency improvement
	Switching from oil to gas heating
	CCS in combination with oxygen
	Increased recycling

Source: IPCC Fourth Assessment Report, Working Group III, Ch 7.4.

Box 8.2 Replacing HFCs in industry

Refrigeration equipment for frozen food processing and storage, industrial production of oxygen and nitrogen, and other cooling processes in industry predominately use ammonia or HCFC-22 as cooling agents. Since HCFCs are due to be phased out under the Montreal Protocol, a shift to HFCs (with high GWPs) is expected. Excellent alternatives exist however in the form of CO_2 (see note 1) or CO_2/ammonia mixtures as coolants. HFCs with very low GWPs, in combination with a leak tight system, could in some cases also be effective. Costs of such alternatives are about US\$30–40/tCO_2-eq avoided.

Foam production for mattresses, furniture, and packaging is currently mostly done with HFCs as so-called blowing agents. Alternatives do exist however in the form of hydrocarbons or CO_2 that can completely replace HFCs at low costs.

In the electronics and other industries CFCs were originally used. After they were banned under the Montreal protocol, water and soap proved to be an excellent replacement for many applications. HFCs and PFCs have replaced CFCs for special purposes, but alternatives are also becoming available.

Note 1: CO_2 has a very low GWP compared to HFCs and HCFCs and given the limited quantities its contribution to overall warming from these applications is completely negligible.

(Source: IPCC Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues related to hydrofluorocarbons and perfluorocarbons, 2005)

Generic reduction options

Apart from the industrial processes we discussed above, there are other types of industrial processes and many small and medium enterprises that contribute a significant amount to industry emissions, mainly from the use of fossil fuel or electricity. They can also contribute to emission reductions, through energy efficiency improvement, fuel switching (either direct fuel use or fuel used in electricity generation), or recycling.

Electric motors are a prime example of what this could mean. In the EU and USA approximately 65% of all industrial electricity use is for electric motors (this includes the sectors that were discussed above). Typical numbers for the energy savings that can be realized by replacing motors with more efficient ones are 30–40%. Investments in such replacements are normally earned back very quickly, after which they produce net benefits. Compressed air systems, widely used in industry, are another example. In general, 20% of such systems are leaking, wasting a lot of energy. With simple measures considerable savings can be achieved. Steam boilers are used in many types of industry. Efficiencies of modern steam boilers are now in the order of 85%, while in practice most boilers are doing much worse. There are many other cheap ways of saving energy through insulation, heat recovery, recycling, proper maintenance of equipment, etc. In particular in developing countries energy savings of 10–20% can be achieved with simple measures. More advanced measures, requiring larger investments, can realize a 40–50% reduction in energy use. Most of these investments have a very short pay-back time.

Recycling of industrial waste materials has a significant potential to reduce emissions. The discussion on the steel industry above showed for instance that recycled steel as input in electric arc furnaces leads to much lower emissions per tonne of steel. Aluminium production from recycled aluminium waste requires only 5% of the energy needed for primary aluminium production. Increasing the recycling rate will therefore reduce emissions significantly. Waste paper as raw material for paper and cardboard manufacture saves energy. Increasing recycling rates to levels of 65% and above (as in Japan and parts of Europe) can realize significant CO_2 emission reduction. Many waste materials can be used as fuel in industrial boilers. If all waste materials were used, this could in theory lead to a 12% reduction of global CO_2 emissions; however, availability at the right place, transport costs, and user requirements will limit this potential considerably.

Renewable energy sources obviously are an important reduction option. In terms of primary energy sources this means use of biomass. The use of sugar cane waste (bagasse) is common in sugar mills. In the paper industry biomass waste is also widely used as an energy source. Increased use of biomass in industrial boilers as a reduction option depends on the local availability of biomass and the way the biomass is produced (see Chapter 9 for a more in-depth discussion). Renewable electricity is of course another good reduction option, as discussed in Chapter 5.

Management of post-consumer waste

Post-consumer solid waste management is schematically given in Figure 8.8. Most of the greenhouse gas emissions come from CH_4 from landfills due to biological conversion of organic waste materials. CO_2 is emitted from incineration and composting, but the fraction from organic (food and plant) residues does not count, because it is supposed to be neutralized by the uptake of CO_2 during growth[11]. CO_2 contributions are therefore small.

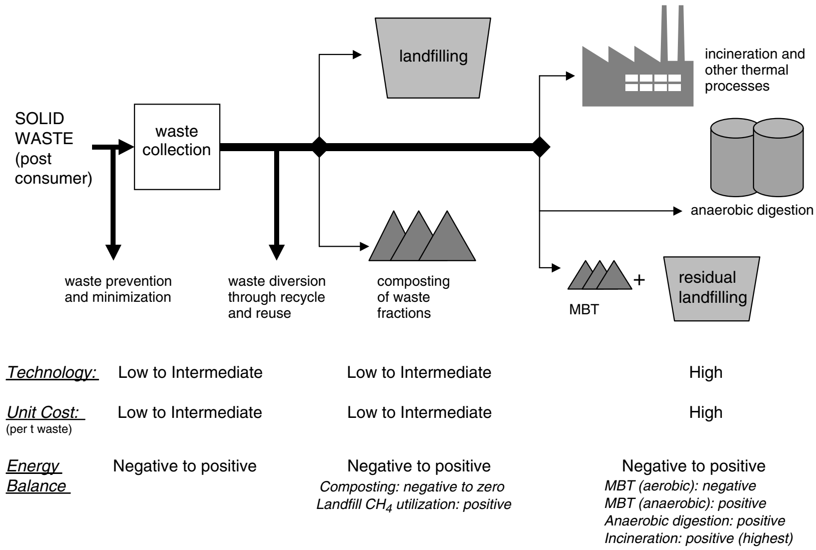

Figure 8.8 **Schematic diagram of post-consumer solid waste management options. MBT = mechanical biological treatment.**

Source: IPCC Fourth Assessment Report, Working group III, figure 10.7.

Reduction of CH_4 emissions from solid waste management can be realized in three ways:

- Waste minimization and recycling, so that less (organic) waste ends up in landfills
- Diversion of (particularly) organic waste to composting, mechanical-biological treatment, anaerobic digestion, or incineration
- Capture of CH_4 from landfills and use as a fuel

The total reduction potential in 2030 is about 0.4–1.0 GtCO_2-eq. Capture of CH_4 accounts for about half of that, with the other two approaches splitting the rest. About half of the potential can be obtained at negative costs, i.e. the benefits of the captured gas outweigh the costs of the measures. About 80% of the total costs less than US$20/t$CO_2$-eq avoided[12].

For waste water management, measures to reduce emissions are first the provision of proper sewerage, septic tanks, and latrines. Water reuse and recycling and shifting to anaerobic waste water treatment can further reduce emissions. Reliable estimates of the potential are not available[13].

Overall reduction potential

The overall reduction potential (direct and indirect) for the industry and waste management sector is about 4.7 GtCO_2-eq/year in 2030, with a fairly large uncertainty margin of plus or

Table 8.4. Overall economic mitigation potential for the industry and waste sector

Mitigation option	Economic potential 2030 ($GtCO_2$-eq/year)	Cost range (US$/$tCO_2$-eq avoided)
Iron and steel	0.4–1.5	20–50
Cement	0.5–2.1	<50
Chemicals and refining	1.0	75% of potential <20
Other industries	0.5–0.6	<100
Generic options	0.1–0.3	<100
Household/office waste management	0.4–1.0	<100
Total	2.9–6.5	<100

Source: IPCC Fourth Assessment Report, Working Group III, Ch 7 and 10.

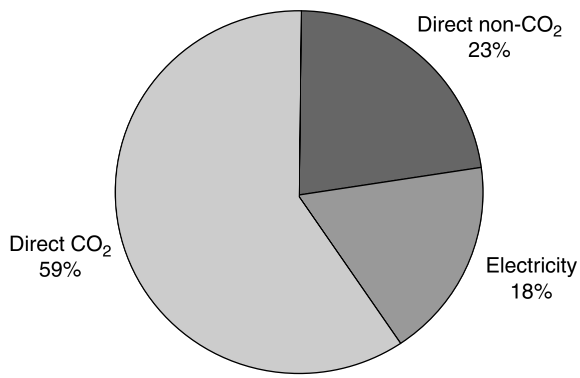

Figure 8.9 Share of direct CO_2 and non-CO_2 and indirect CO_2 reduction in the economic reduction potential of the industry and waste management sector.
Source: IPCC Fourth Assessment Report, Working Group III, Ch 7 and 10.

minus 1.8 $GtCO_2$-eq. This is at cost levels up to US$100/$tCO_2$-eq. Of this potential about 30% can be obtained at costs lower than US$20/t, about 90% at costs below US$50/t. It means a reduction of 15–40% of emissions in 2030 without mitigation. The composition of the reduction potential is shown in Table 8.4.

The distribution between direct CO_2 and non-CO_2 reduction and indirect reduction from electricity use is shown in Figure 8.9.

Costs referred to above are strictly for the reduction measures taken and do not account for additional benefits (so-called co-benefits) achieved. Experience shows that energy efficiency programmes very often lead to improved maintenance and therefore reduced down-time of equipment, leading to better product quality, less waste, and better use of existing equipment. In a study of co-benefits in about 50 projects in several countries, costs of GHG reduction measures were cut in half when co-benefits were counted. Overall numbers for cost reduction from co-benefits are not available.

As indicated above, the reduction potential in industry in the longer term is higher than for 2030. By 2050 greenhouse gas emissions could be reduced by more than 60% compared to the baseline, when going up to cost levels of US\$200/tCO_2-eq avoided. For comparison, by 2030 and costs <US\$100/tCO_2-eq it is less than 40%.

How to make it happen?

Investment decisions in larger companies in industry are made on rational economic grounds. Given strong competition and global markets, companies cannot afford to do otherwise. This means that investments in greenhouse gas emission reduction are only made when there are economic benefits. Benefits can be a lowering of energy costs when investing in energy efficiency improvement. It can also be in the form of increased shareholder value, when a company takes the lead in climate change mitigation. BP experienced that when it undertook to lower its CO_2 emissions by 10% and Dupont's goal of cutting its GHG emissions by 65% was made part of its efforts to become a leader in sustainable growth.

Where CO_2 has a price, such as in the EU under the European Emission Trading System, economic benefits are obtained by lowering emissions in order to avoid purchasing additional emission allowances. Or, when there are regulations to use best available technologies, such as under the EU Integrated Pollution Prevention and Control Directive, the economic benefits of investing are avoiding penalties. Profitability of investments in industry is normally judged in terms of their pay-back time (the time needed to recoup the investment). Generally in industry only investments with pay-back times of not more than a few years are approved. The economic logic means that emission reduction investments that do not meet those private sector pay-back criteria are simply not made. Subsidies provided by governments will of course make investments more attractive.

The lifetime of facilities in industry is often tens of years, which slows the penetration of low-emission equipment and process plants (this is the so-called 'slow capital stock turnover'). Replacing an installation before the end of its economic life is economically difficult to justify, unless the alternative is very attractive.

Industry also rates the reliability of installations highly and is therefore reluctant to invest in new equipment that does not have a long track record, even when the pay-back time of the investment looks good. Banks are often reluctant to provide loans for new technologies, even if the company is convinced of its viability. Particularly in SMEs there are problems of lack of expertise or time to evaluate alternatives that slow down the acceptance of new technologies. In larger companies strategic consideration about mergers or acquisitions could take the attention away from economically justifiable investments.

Applying commercially available technologies across a whole industrial sector is a time consuming process therefore. In many developing countries there are additional problems with respect to technical capacity, availability of capital, and unattractive investment conditions. Modern technologies often have to be acquired abroad, which further complicates investments in modern low emission technologies (the so-called technology transfer problem[14]). This means that even profitable investments are not always made. In other words, many greenhouse gas emission reduction technologies are not taken up as much as the economic benefits would justify.

Policy instruments

Policy instruments are needed to make investments attractive. There are basically four approaches:

1. Make it more attractive to invest in profitable reduction measures
2. Make unprofitable investments profitable by creating incentives
3. Increase the price of greenhouse gas emissions to make more advanced technologies profitable (or require those through regulation)
4. Stimulate R&D to develop future mitigation technologies or make current ones cheaper

These policy instruments are discussed in Chapter 11, but the specific experiences in applying them in the industry and waste sector are outlined below.

Voluntary agreements

An instrument belonging to the first category is the so-called voluntary agreement between (a sub-sector of) industry and a government. They have been used in a number of industrialized countries since the early 1990s. They are essentially negotiated contracts, containing targets to be met by industry (often in terms of energy efficiency) and facilities and support to be provided by governments (for analyzing performance, information sharing, recognition, awards, etc). They vary in terms of the stringency of the targets, but more importantly in the verification and penalty provisions. Experience shows that agreements with a credible threat of regulations or taxes in case the agreement does not work, and with adequate government support, are the most effective (mainly in Japan and the Netherlands, see also Chapter 11). In such cases the effect is that pay-back criteria for low emission investments are somewhat relaxed. Generally speaking, voluntary agreements raise awareness in industry about the possibilities for GHG emission reduction and reduce barriers against low emission investments, such as the lack of information. However, for most voluntary agreements no difference from a business as usual improvement could be detected.

Industry initiated voluntary actions

Many companies have taken on actions related to reduction of greenhouse gas emissions on a strictly voluntary basis, without involvement of governments. Some, like Dupont, BP, and United Technologies Corporation, have achieved measurable reductions in energy use or emissions (see Box 8.3). Others have joined international initiatives, such as the Global Reporting Initiative (measuring and reporting of GHG emissions), the World Business Council for Sustainable Development's Cement Sustainability Initiative (CO_2 inventories and best practice sharing), the International Aluminium Institute's Aluminium for Future Generations programme (technical services, performance indicators, reduction objectives), and the International Iron and Steel Institute's voluntary action plan (measuring and reporting CO_2 emissions, general objectives for reduction of energy use and emissions).

Environmental NGO's like the World Wildlife Fund and the Pew Center on Global Climate Change increasingly work with companies to help them formulate voluntary actions.

Box 8.3 **Some corporate achievements**

Dupont is a chemicals company with 135 facilities in 70 countries, 60 000 employees and about US$60 billion in sales. It formulated the following company-wide targets:

- Reduce greenhouse gas emissions by 65% below 1990 levels by 2010
- Hold total energy consumption at the 1990 level
- Supply 10% of energy from renewable sources

Energy use was indeed kept at the 1990 level through an aggressive energy efficiency improvement programme, involving company-wide training and energy audits. It also resulted in a net cost reduction by the way. By 2002 the emission reduction target had already been met. In 2004 reductions were 72%. It was achieved by eliminating N_2O emissions from adipic acid manufacturing (a raw material for nylon) and HFC-23 emissions from the production of HCFC-22 (a cooling liquid). With 80% of Dupont's emissions from N_2O and HFC-23, and energy related CO_2 emissions remaining constant, this helped them to meet the target.

In 1998 BP set a target of reducing company-wide direct greenhouse gas emissions (i.e. from operations only, not from burning the fuels BP produces) by 10% below 1990 values. In 2002 this target was met. In 2007 emissions had declined further. Most reductions were achieved through reduced flaring and venting and improvements in energy efficiency. They also resulted in net cost reductions.

(Source: IPCC Fourth Assessment Report, Working Group III, ch 7; Dupont testimony US Congress, http://oversight.house.gov/documents/20070523104438.pdf; BP Sustainability Report, 2001, 2006, 2007, http://www.bp.com/sectiongenericarticle.do?categoryId=90222142&contentId=7041069)

Most voluntary actions result in the implementation of economically profitable emission reductions. Since these are often not implemented under normal circumstances, this is a contribution to mitigation in the industry sector. However, as substantial emission reductions are needed in the future, voluntary actions and voluntary agreements will be unable to deliver these in the absence of strong government action.

Financial instruments

Financial instruments come in different forms: taxes, tax deductions, and subsidies.

Taxes on CO_2 emissions from industry have only been introduced in a limited number of countries so far. Norway has a CO_2 tax of about US\$50/tCO_2. It mainly applies to the off-shore oil and gas industry, since many other industry sectors were exempted in exchange for committing to voluntary agreements on emission reduction. The Stattoil CO_2 capture and storage installation at its Sleipner gas production platform became attractive just because of this tax. Sweden has a carbon tax of about US\$40/tCO_2, but industry pays only half. The same holds for Denmark, but with a much lower rate of US\$14/tCO_2[15]. The UK introduced a general climate change levy (less than 1USc/kWh), but then created exemptions for industries that participate in voluntary agreements or emission trading. France has a modest tax on N_2O emissions from chemical industries. Industry in the Netherlands only pays energy/CO_2 tax up to a relatively small volume of electricity and gas usage. It is exempted from the rest. Germany introduced a similar eco-tax. The reason for all these exemptions (and the lobbying by industry for it) is the effect the taxes have on international competitiveness. Due to their limited impact, taxes have not achieved much in terms of moving to emission reductions with net positive cost. There is one clear exemption: the Norwegian tax on offshore oil and gas operations that led to the introduction of CCS. Taxes do contribute however to taking cheap reduction options more seriously.

Tax deductions are quite popular in many countries to encourage industry investments. They often however fail to discriminate between investments in reducing greenhouse gas emissions and other more traditional investments. So the impact of tax deductions is hard to assess. Effectiveness requires a quite precise description of investments the tax deduction applies to. Recent energy efficiency oriented tax deduction schemes in The Netherlands, France, and the UK are trying to do that[16].

Subsidies for investments by industry in energy efficient equipment in the form of grants or cheap loans are quite popular. In Europe, Japan, and Korea extensive programmes exist. Evaluations of such subsidy programmes generally show a positive influence on energy savings and corresponding emission reductions. They also show a positive influence on the development of markets for innovative technologies. The major drawback of these subsidy schemes is that they also benefit companies that would have made the investments anyway. That particularly applies to investments that deliver net profits. To make subsidy schemes more effective, targeting positive cost technologies is very important. In developing countries subsidy schemes for industry are generally lacking, making the role of commercial and development banks all the more important. Unfortunately these institutions are often not equipped or willing to give priority to loans for energy efficiency investments.

Cap and trade programmes

Cap and trade means setting maximum emission levels for companies and then allowing them to trade emissions allowances between themselves to fulfil their obligations.

A company that can reduce its emissions below the maximum can sell surplus allowances to others. A company that finds it too expensive to reduce its own emissions can buy allowances to fulfil the obligation. In doing so, a price for emitting a tonne of CO_2 will emerge. The more stringent the emission limits, the higher the price. If the market works well, i.e. companies do indeed trade surplus allowances and other companies do buy allowances, the overall cost of realizing the emission reduction will be minimized. The cheapest options are then done first.

The first big application of a cap and trade system happened in the USA in the 1980s under the Clean Air Act, when companies were allowed to trade SO_2 allowances. Greenhouse gas cap and trade systems are in operation in the EU (see Chapter 11 and Box 11.5), Norway (Norway will join the EU trading system soon), New South Wales (Australia), and several US States. Australia, New Zealand, Japan, and the USA are considering introducing national systems. Energy intensive industries are always included.

Cap and trade systems so far apply mostly to large installations. The EU ETS for instance covers over 11 500 energy-intensive installations across the EU, which represent about 40% of Europe's emissions of CO_2. These installations include combustion plants, oil refineries, coke ovens, iron and steel plants, and factories making cement, glass, lime, brick, ceramics, pulp, and paper. The chemical industry was only partially included through their large combustion unit or their integration with petroleum refineries. For the period after 2012 ammonia and aluminium plants and N_2O and PFC from some industrial sources are also included[17]. For smaller installations the administrative burden becomes bigger and so these are usually left out of the cap and trade system. In theory there are ways to bring these smaller entities into the system by allocating the allowances to suppliers of natural gas or other raw materials.

A big issue under any cap and trade system is the initial allocation of emission allowances. Most systems in operation today started on the basis of free allocation only, based on historic emission levels (so-called 'grandfathering'). This was very much pushed for by industry in light of international competitiveness. To some extent actual performance of the plant, in terms of previous reduction measures, can be taken into account. In the EU ETS this is done at the Member State level in the so-called national allocation plans. Normally there are provisions made for newcomers: if a new company wants to build a production plant there are guarantees that they can obtain the necessary emission allowances.

Gradually, a shift towards auctioning the allowances is visible. In the EU ETS during the period 2008–2012, Member States have the option of auctioning up to 10% of the allowances[18]. For the period after 2012 more auctioning will take place. For non-exposed industries 70% will be auctioned by 2020, increasing to 100% by 2027[19]. Most systems under consideration elsewhere also incorporate partial or full auctioning. Auctioning means companies have to buy the allowances at a market price, which adds to the cost of their operation. That is why globally competing companies that are subject to the EU ETS are lobbying hard to be given the allowances for free. There is a tendency however for them to exaggerate the impacts. As indicated above energy only forms a significant part of total operating costs in a limited number of industrial sectors.

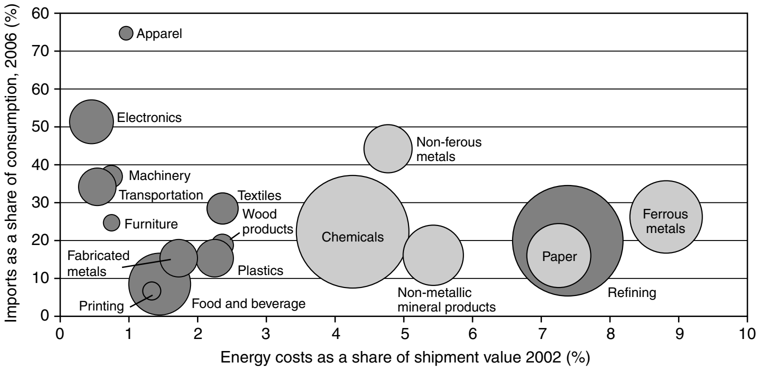

Figure 8.10 **US industry exposure to climate costs. Sectors that have high energy costs and are faced with large imports are the most vulnerable to competition. The size of the bubbles is proportional to the CO_2 emissions in 2002.**

Source: Houser et al. Levelling the carbon playing field, Peterson Institute for International Economics and WRI, 2008.

And the exposure to international trade also varies: it is high for aluminium, moderate for chemicals, oil products, paper and steel, but low for cement, glass, and ceramics. In response to industry concerns it has been decided to exempt certain industry sectors from auctioning of permits if they face high cost increases and are very exposed to trade[20]. Figure 8.10 shows the situation for US industry.

The most important lesson that was drawn from the EU ETS operation so far is the fact that more centralized allocation of allowances is needed. The system with 27 national allocation plans led to big differences in treating similar installations in different Member States. It has been decided therefore to replace this with one central allocation system, run by the Commission.

Regulation

Regulation on industrial greenhouse gas emissions is applied on a limited scale. In the EU the system of permitting large industrial installations, based on the Integrated Pollution Prevention and Control (IPPC) directive, covers N_2O and fluorinated gas emissions from some installations. It requires Best Available Technology standards to be applied (based on BAT reference documents issued by the European Commission[21]). In the EU and some other countries there are also regulations banning the use of HFCs, PFCs, and SF_6 in certain applications. China is using regulation to force the closure of a substantial number of old, inefficient cement plants[22]. It remains to be seen how much of this plan will be implemented. In general the notion of forced closing of outdated inefficient plants is a useful one to consider as part of a portfolio of policies to realize substantial emission reductions. It could for instance be part of a system of mandating Best Available Technologies in industry at the national level.

Technology policy

There are extensive policy efforts aimed at diffusion and transfer of modern efficient technologies and at developing new and better technologies. They normally are not seen as climate change related, but they in fact are. So it is good to discuss what these technology policies could mean for realizing deep reductions in greenhouse gas emission from industry.

An efficient plant, in terms of energy and raw materials use, can produce at lower costs than an inefficient plant. That means a better competitive position, which is good for the economic development of a country. That is why government policies to promote the application and development of modern efficient technologies exist.

Since technology policy also affects the energy, transportation, and buildings sector technology policies will be discussed in more detail in Chapter 11.

Air and water regulations

Controlling air pollution from sulphur oxides, nitrogen oxides, and fine particles can also reduce CO_2 emissions if focussing on energy efficiency improvements and fuel shifts (from coal to gas or renewable energy sources). So air pollution control policies can have an impact on reducing CO_2 emissions in industry. There is a tendency to integrate air pollution and climate change policy in order to maximize the win-win opportunities. Particularly in Europe, under the UN Convention on Long Range Transport of Air Pollution and under EU policy, this is being pursued. In many other places however air pollution is often controlled with add-on desulphurization units and particle filters that tend to increase energy use and CO_2 emissions.

Waste management

Waste management is to a large extent a government dominated and local industry. Competitiveness hardly plays a role. It is also dominated by health and environment considerations, which means that waste management rather than climate policies are the appropriate instrument. If we look at the biggest reduction opportunity, i.e. avoiding CH_4 from landfills, then it obvious that regulations on landfill construction and CH_4 capture are fundamental. But since the other half of the potential lies in avoiding waste and diverting it to other waste processing methods, policies also need to be focussed on that. The most effective approaches to reduce waste and encourage recycling are financial incentives (e.g. buy special waste bags for a price that reflects the disposal costs; no other bags allowed) and regulations (ban on recyclables in general waste, combined with collection of recyclables). In many places municipal governments are still relying on purely voluntary approaches through information and central recycling centres. These voluntary approaches are often reasonably successful, but fail to capture all of the potential[23].

More recycled material as input for steel and aluminium making, paper production, and plastic processing has immediate effects on industrial energy requirements and CO_2 emissions. Recycling also provides fuels for industrial boilers and cement plants, replacing fossil fuels. Effective waste management and recycling policies can therefore have a positive impact on realizing reduction of industrial emissions.

Future challenges

Big greenhouse gas emission reductions are possible in industry at reasonable costs. The greatest challenge is to realize these reductions, given that industry operates in a competitive environment. Many energy intensive products are traded internationally, if not globally. Forcing industry in some countries to drastically reduce emissions while competitors elsewhere are not facing restrictions will therefore not solve the problem. In practice this slows down the implementation of reduction options, because pushing companies to relocate and losing jobs is not an attractive proposition for politicians. The solution is either to develop international agreements covering most competitors, or to use trade mechanisms to protect domestic industries that face strict emission reduction obligations.

Waste management can make a large contribution when both industrial waste and waste water streams as well as so-called post-consumer waste are considered. The numbers usually point to waste treatment options such as capturing CH_4 from landfills as the most important ones. However, minimizing waste by reducing the material content of products and maximizing recycling are undervalued. At present we do not know enough about the reduction in energy use and greenhouse gas emissions from such dematerialization and ‘cradle to cradle’ approaches. More studies, in particular life cycle analyses that look at complete lifecycles of products, should provide better answers in the future.

Notes

1. IPCC Fourth Assessment Report, Working Group III, ch 7.1.2.
2. Houser et al. Leveling the carbon playing field, Peterson Institute for International Economics and WRI, 2008.
3. IPCC Fourth Assessment Report, Working Group III, ch 10.2.1.
4. IPCC Fourth Assessment Report, Working Group III, ch 10.1.
5. IPCC Fourth Assessment Report, Working Group III, ch 7.1.3 and 10.3.
6. Coke is ‘degassed’ coal, produced by heating coal in the absence of air, so that it loses its volatile compounds (methane, hydrogen, carbohydrates, and tar). Coke has a porous structure that gives it ideal properties for binding oxygen from iron ore in blast furnaces.
7. IPCC Fourth Assessment Report, Working Group III, ch 7.4.1.
8. IEA Energy Technology Perspectives, 2008, ch 16 and IPCC Fourth Assessment Report, Working Group III, ch 7.3.7.

9. IEA Energy Technology Perspectives, 2008, ch 16.
10. See note 8.
11. Plants take up CO_2 during growth from the atmosphere. When they are incinerated, CO_2 returns to the atmosphere. This process is thus a closed loop and net emissions are zero.
12. IPCC Fourth Assessment Report, Working Group III, ch 10.4.7.
13. IPCC Fourth Assessment Report, Working Group III, ch 10.4.6.
14. See IPCC Special Report on Methodological and Technological Aspects of Technology Transfer, 2005.
15. http://www.carbontax.org/blogarchives/2008/03/.
16. IPCC Fourth Assessment Report, Working Group III, ch 7.9.3.
17. http://ec.europa.eu/environment/climat/emission/ets_post2012_en.htm.
18. See for more detail Hepburn C et al. Climate Policy, vol 6, 2006, 137–160.
19. See note 17.
20. IEA, Issues behind competitiveness and carbon leakage: focus on heavy industry, 2008.
21. http://ec.europa.eu/environment/air/pollutants/stationary/ippc/index.htm.
22. IEA, Sectoral approaches to greenhouse gas mitigation: exploring issues for heavy industry, 2007; see also note 2.
23. IPCC Fourth Assessment Report, Working Group III, ch 10.5.